Lithium Lorentz Force Accelerator Research at Princeton

Advanced Space Propulsion Workshop

April 3-5, 2001

Huntsville, AL

The LiLFA Research Team

At Princeton University

Kamesh Sankaran	Graduate Student, EPPDyL
Andrea Kodys	Graduate Student, EPPDyL
Leonard Cassady	Graduate Student, EPPDyL, National Defense Science and Engineering Fellow, Francis Upton Fellow
Prof. Edgar Choueiri	***Chief Scientist***, EPPDyL

Visiting from Ecole Polytechnique

Gregory Emsellem	Graduate Student, Laboratoire de Physique des Milieux Ionisés

Sponsors

NASA-JPL's Advanced Propulsion Group

Princeton Plasma Physics Laboratory's Program in Plasma Science and Technology

Research Tasks

Experimental, analytical and numerical, studies in support of NASA-JPL's MWe LiLFA research program

- *Fundamental Processes*
  - Anode losses and thermal management
  - Multi-channel hollow cathode physics studies
  - Performance limiting phenomena
  - Scaling Laws
  - Lithium exhaust flux characterization
- *Technology and Tool Development*
  - Lithium handling facilities
  - Neutralization, disposal and emergency procedures
  - Lithium feed system development
  - Specialized diagnostics
  - Advanced flow simulation code

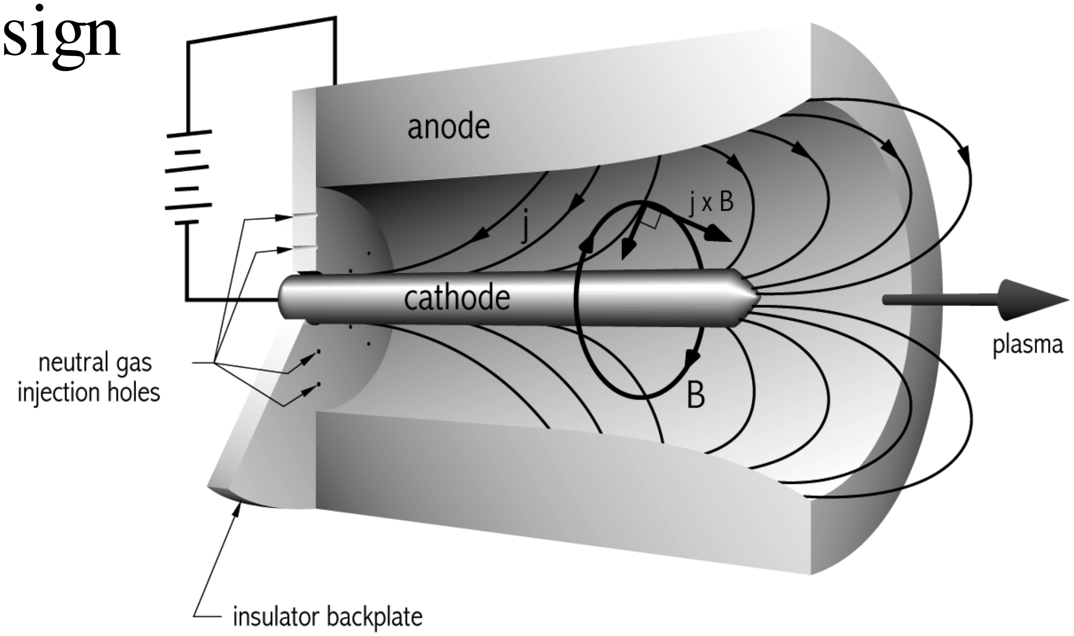
Fundamental Scaling Law

Allows studies of MW self-field thrusters to be conducted at moderate powers

$$\xi = \frac{J}{\left[\dfrac{\dot{m}^{1/2}(2\epsilon_i/M)^{1/4}}{\dfrac{\mu_0}{4\pi}\ln\dfrac{r_a}{r_c}}\right]}$$

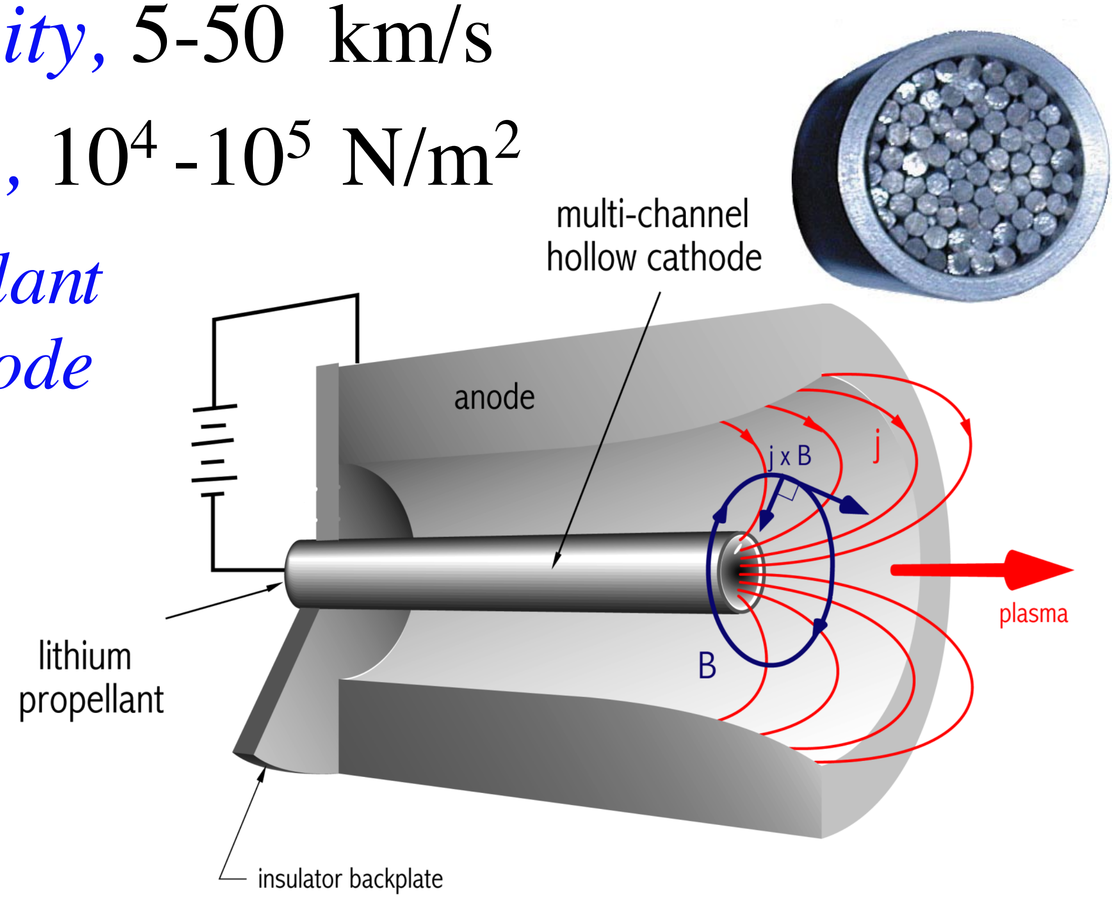
The Self-Field MPDT

- Lorentz force ***(j x B)*** acceleration
- High *exhaust velocity*, 5-50 km/s
- High *thrust density*, 10^4-10^5 N/m^2
- Robust and simple design
- Solid cathode
- Gaseous propellant injected at backplate
- Current attachment along entire cathode



The Lithium Lorentz Force Accelerator

- High *exhaust velocity*, 5-50 km/s
- High *thrust density*, 10^4-10^5 N/m^2
- *Lithium vapor propellant injected through cathode*
- *Multi-channel hollow cathode (MCHC)*
- *Improved efficiency,*
  - 50% at 200 kW.
- *Reduced erosion,*
  - 500 hours of erosion-free operation.



Why Lithium Propellant?

- *Electrode erosion* limits lifetimes of MPDTs well below current mission requirements

  ⇒ Lithium coverage shown to *lower the work function* of the electrode metal

- Energy lost in *multiple ionization* limits efficiency

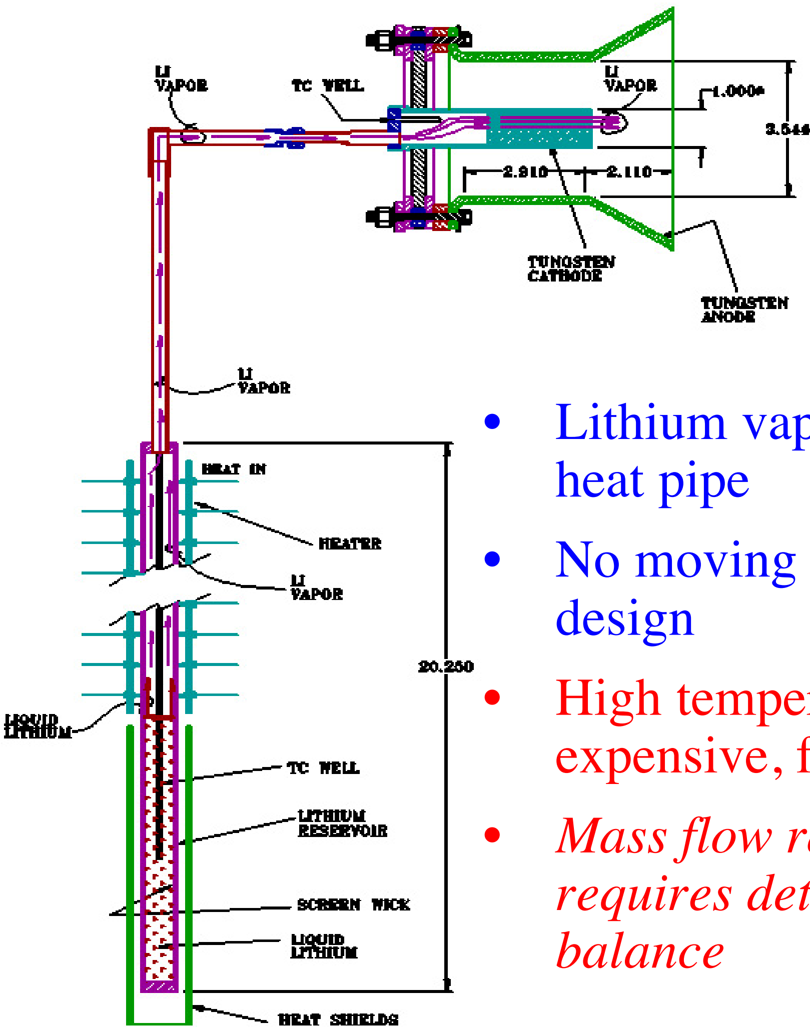
  ⇒ Lithium has a *low first* and a *high second* ionization potential

- Space and energy required for *storage of propellant*

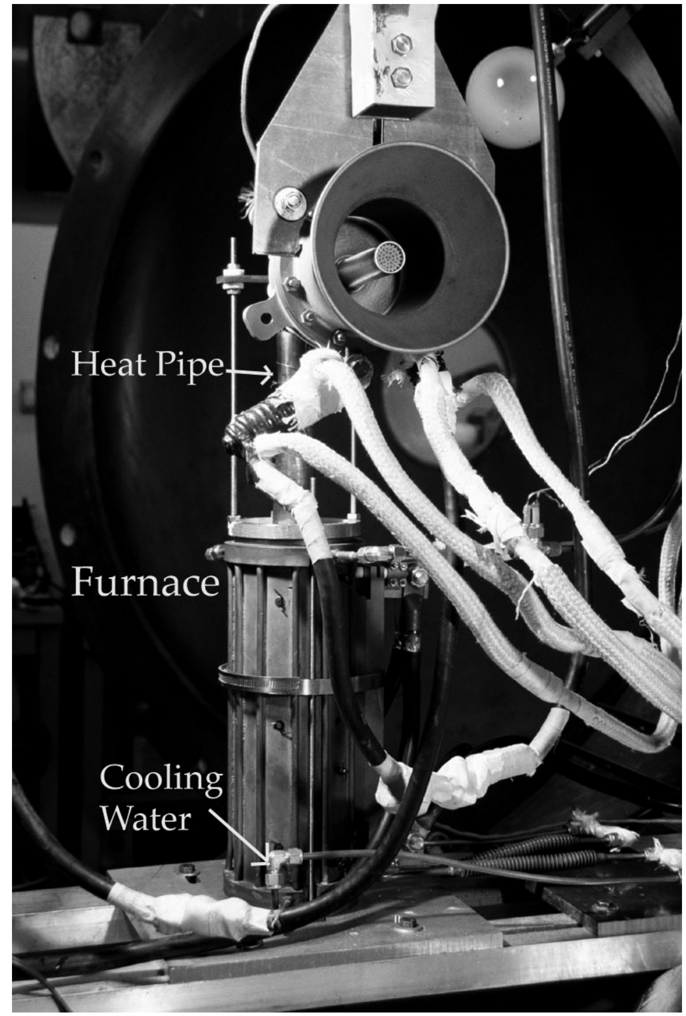
  ⇒ Lithium *stored as a solid* and vaporized before use

Use lithium as propellant ⟺ *Lithium handling issues*
Complexity of feed system design

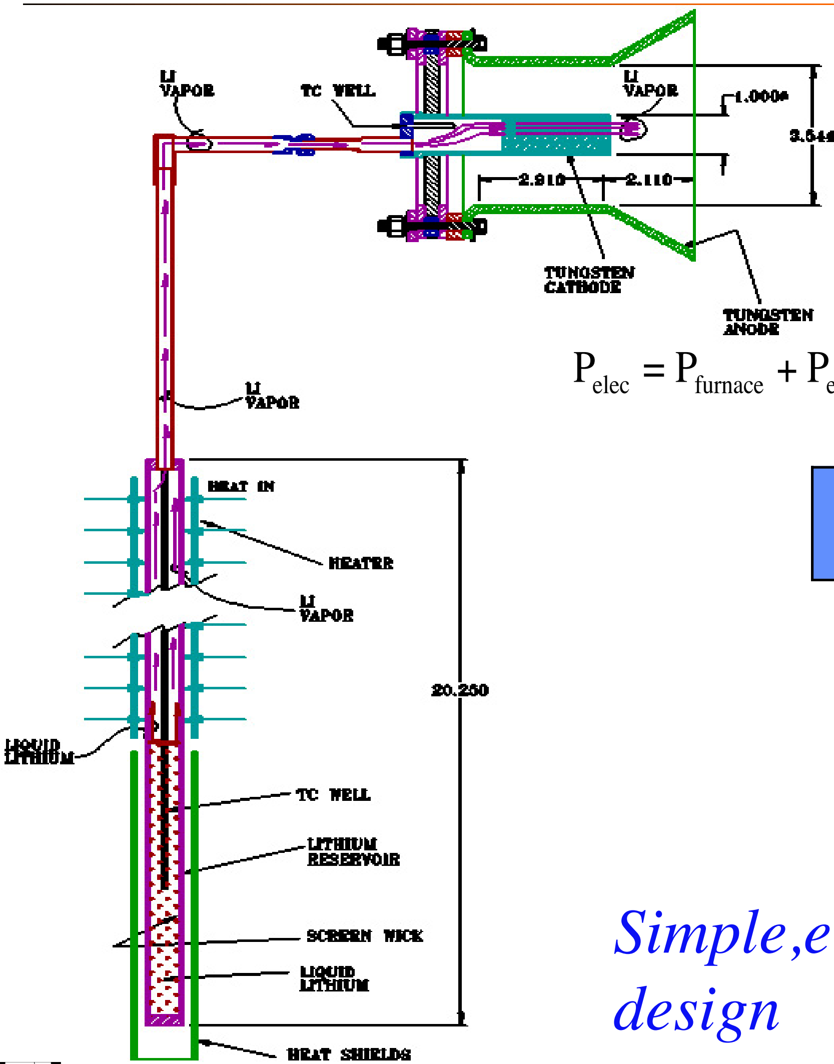
Open Heat Pipe Feed System Principle



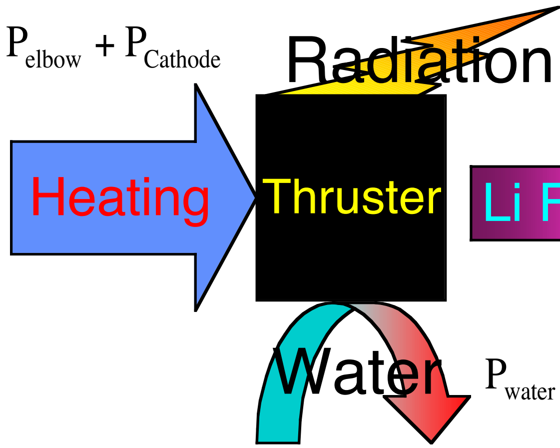
- Lithium vapor fed via open heat pipe
- No moving parts, simple design
- High temperatures require expensive, fragile materials
- *Mass flow rate estimation requires detailed power balance*



Open Heat Pipe Feed System Principle



$$P_{elec} = P_{furnace} + P_{elbow} + P_{Cathode}$$



$$P_{tank} = \iint_{thruster} \sigma\varepsilon_{(x,y,z)} T^4_{(x,y,z)} dS$$

$$P_{Li} = \dot{m}_{Li}\lambda_{Li}$$

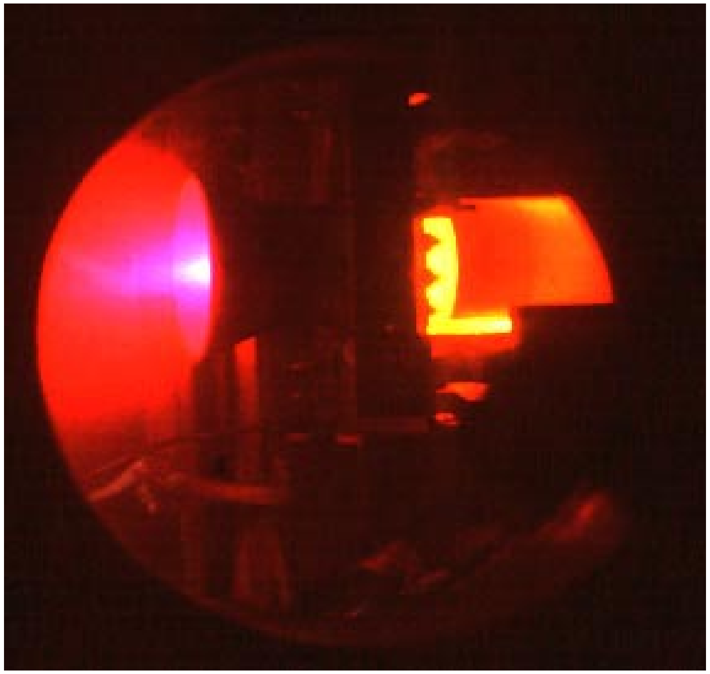
$$P_{water} = \dot{m}_{H_2O} . C_{H_2O} . (T_{in} - T_{out})$$

Simple, elegant design ⟺ *Limited flow rate control*
Difficult construction

Proof of Concept of Open Heat Pipe Design

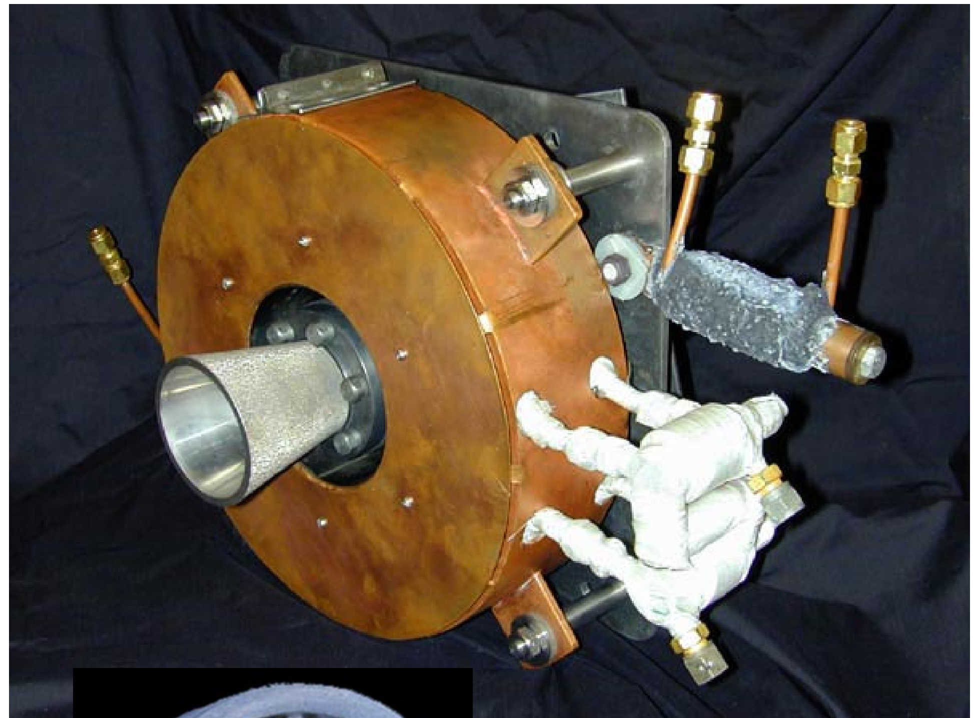
The open heat pipe feed system concept was successfully demonstrated

Thruster power	6 kWe +/-11%
Mass flow rate	1 mg/s
Measured Thrust	24 mN +/- 43.5%
Predicted Thrust (Maecker)	25.74 mN +/-10%
Thrust efficiency	< 5%



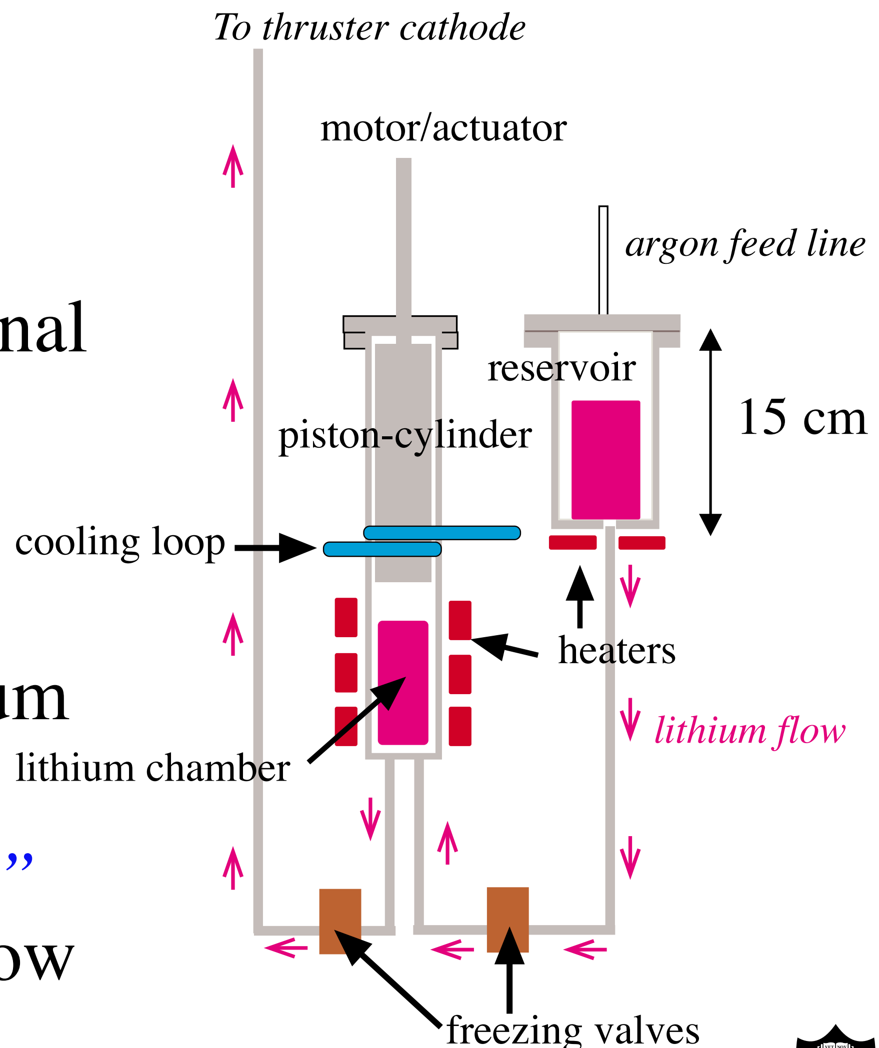
Moscow Aviation Institute 30kWe LiLFA

- *Fundamental studies require greater accuracy and control of lithium flow rate*
- Propellant vaporization within MCHC
- Requires liquid lithium feed to vaporizer cathode



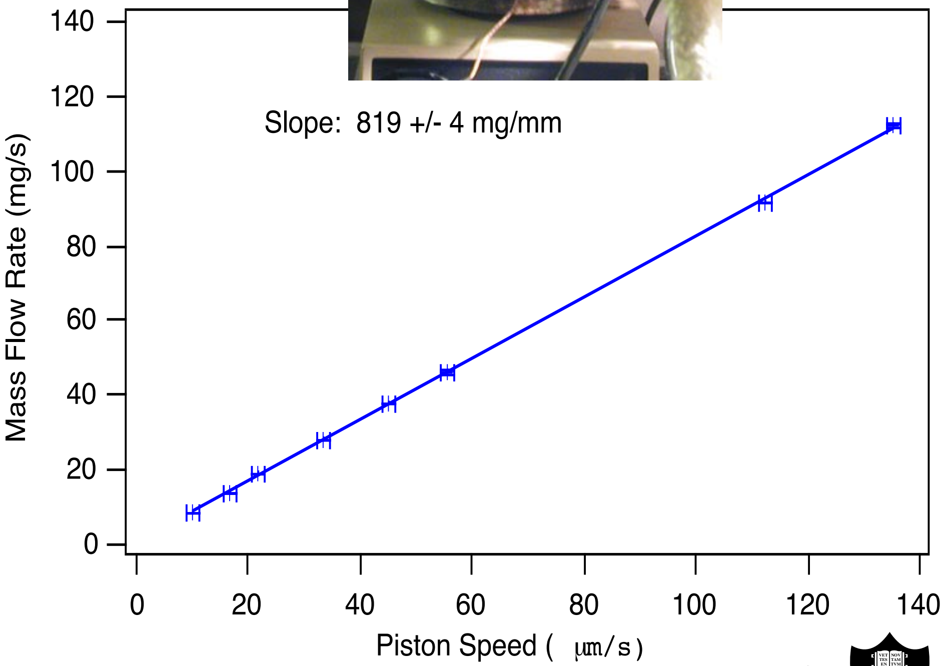
Lithium Mass Flow Control System

- *Mechanically* driven piston provides *liquid* lithium to vaporizer cathode
- Lithium flow rate proportional to piston speed
- Operating temperature: 250-300 C
- Cooling loop prevents lithium leakage
- Innovative *"freezing valves"* thermally control lithium flow

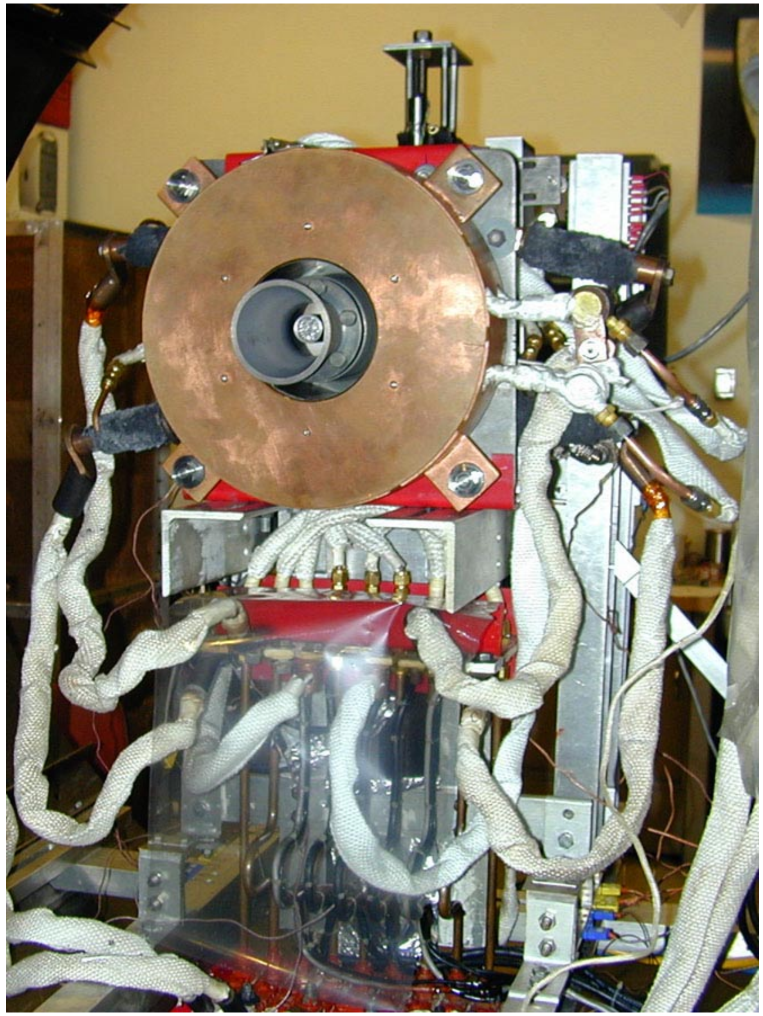


Lithium Feed System Calibration

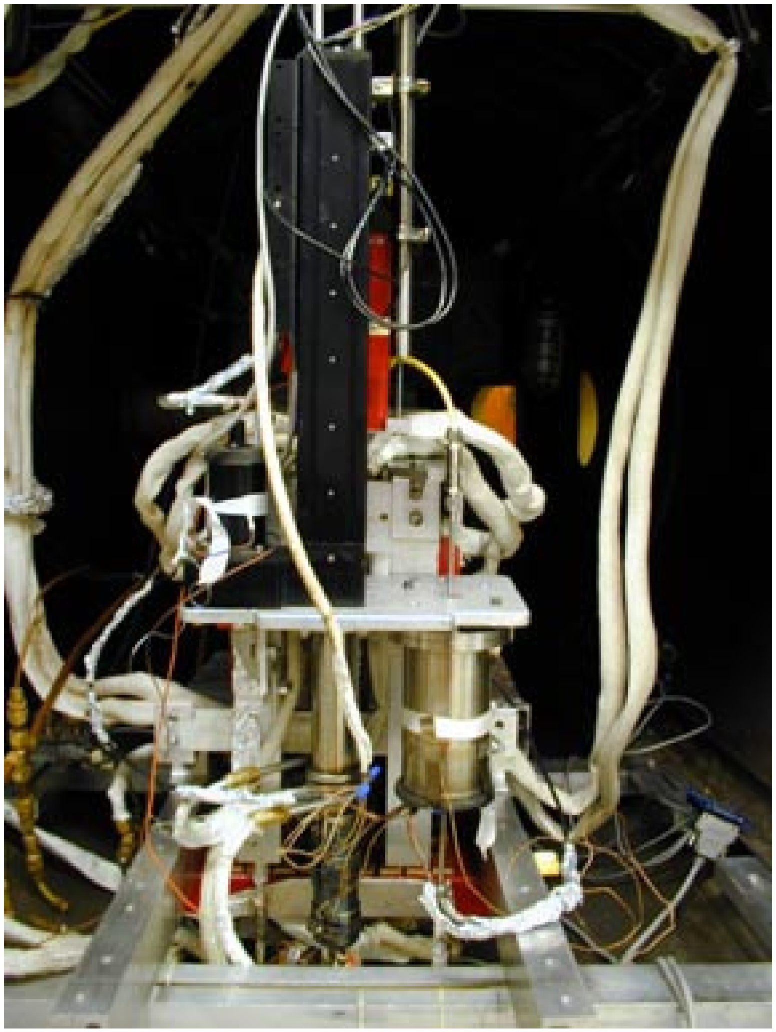
- √ Demonstrated ability to track lithium state and flow
- √ Obtained freezing valve and cooling loop design proof of concept
- √ Determined linear relation between piston speed and lithium flow rate

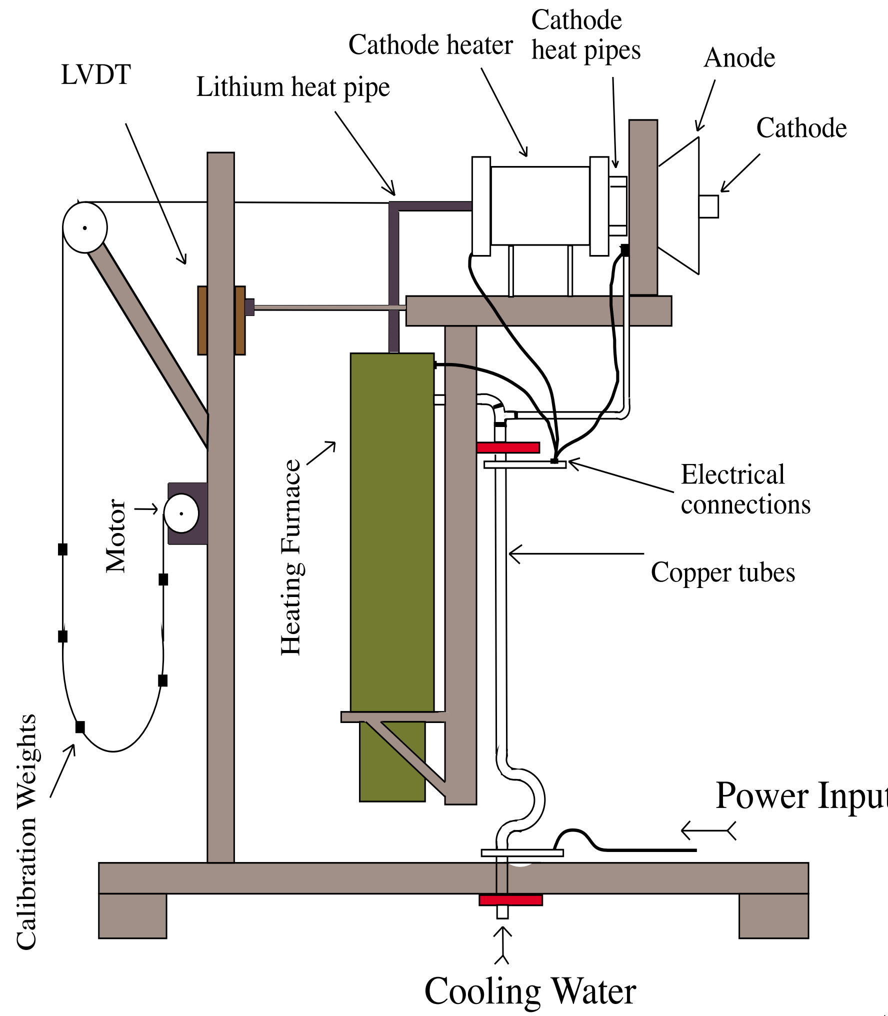


System is Ready for Detailed Studies

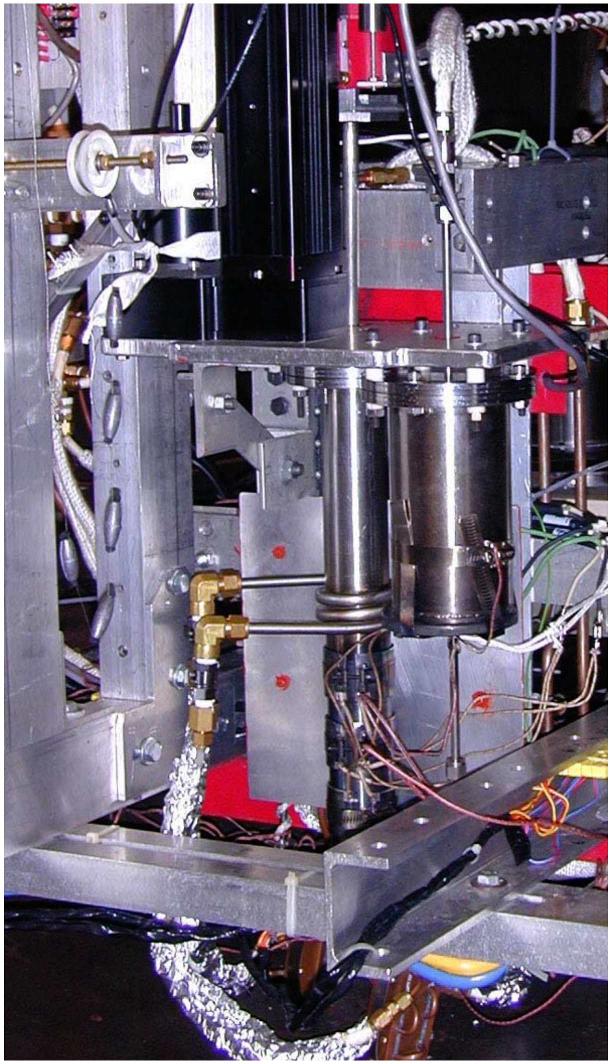


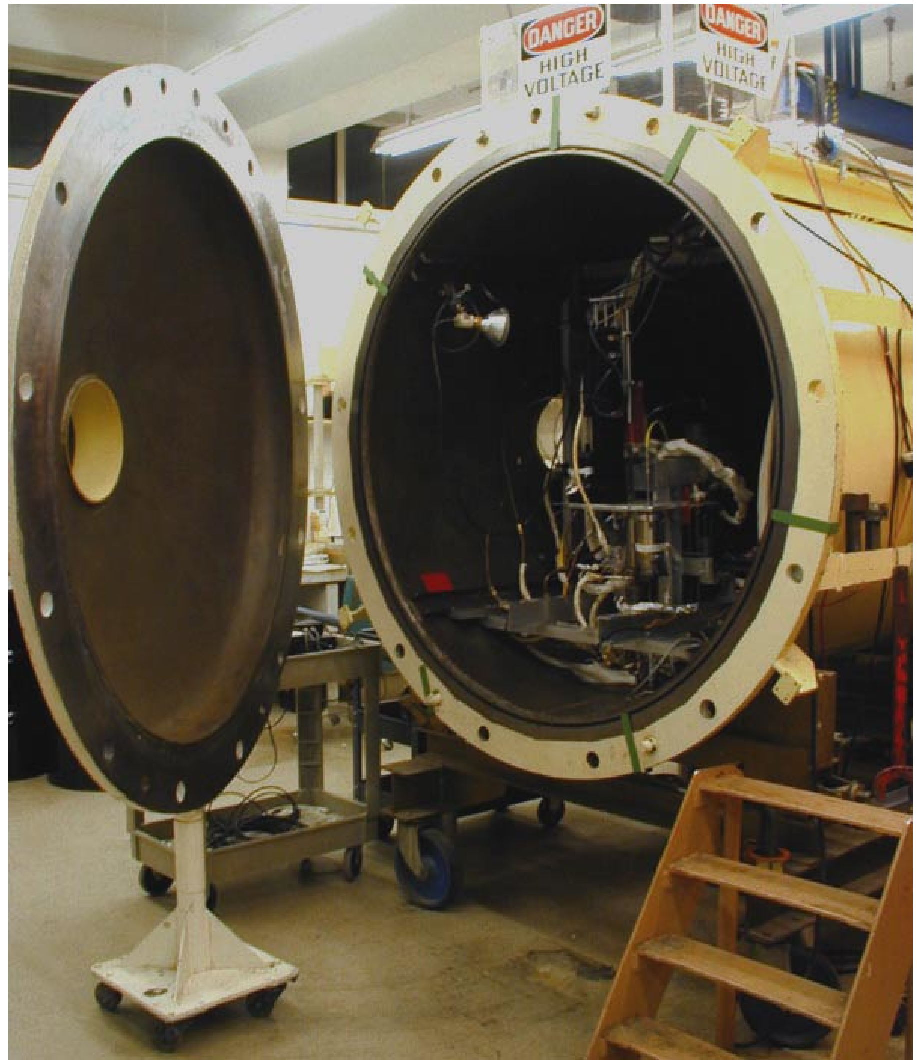
High-power Steady-state Thrust Stand





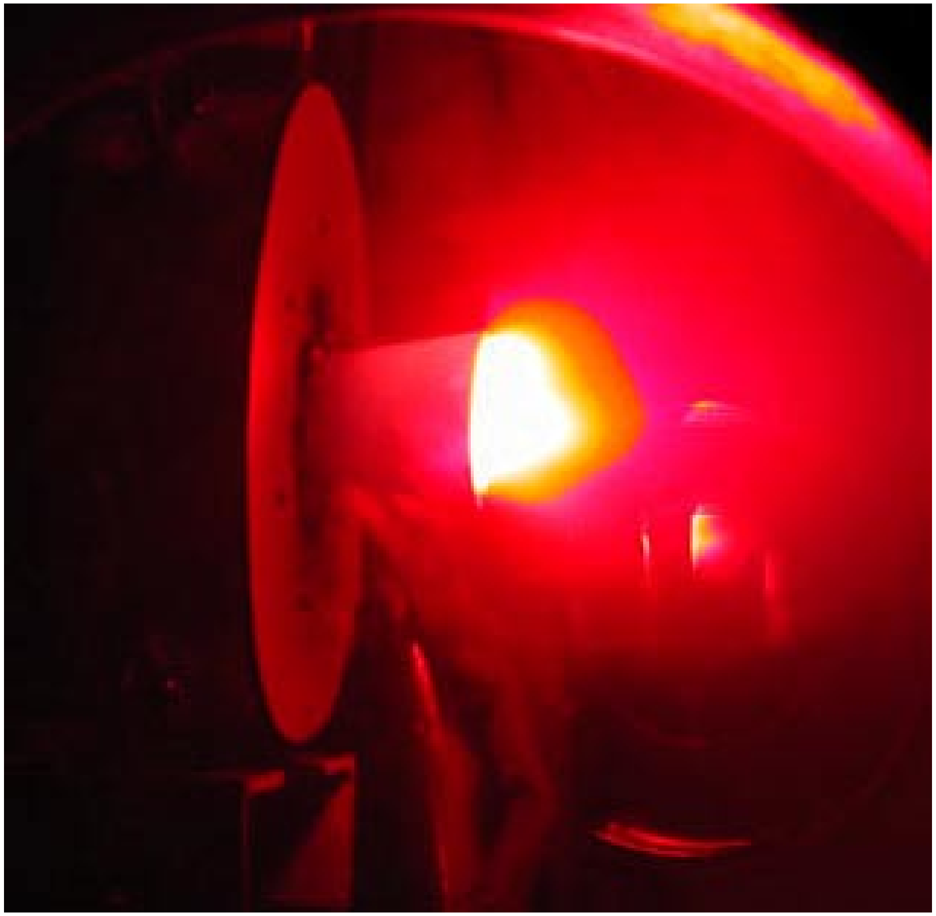
Lithium Feed System in Testing Facility





Successful Firing of New LiLFA

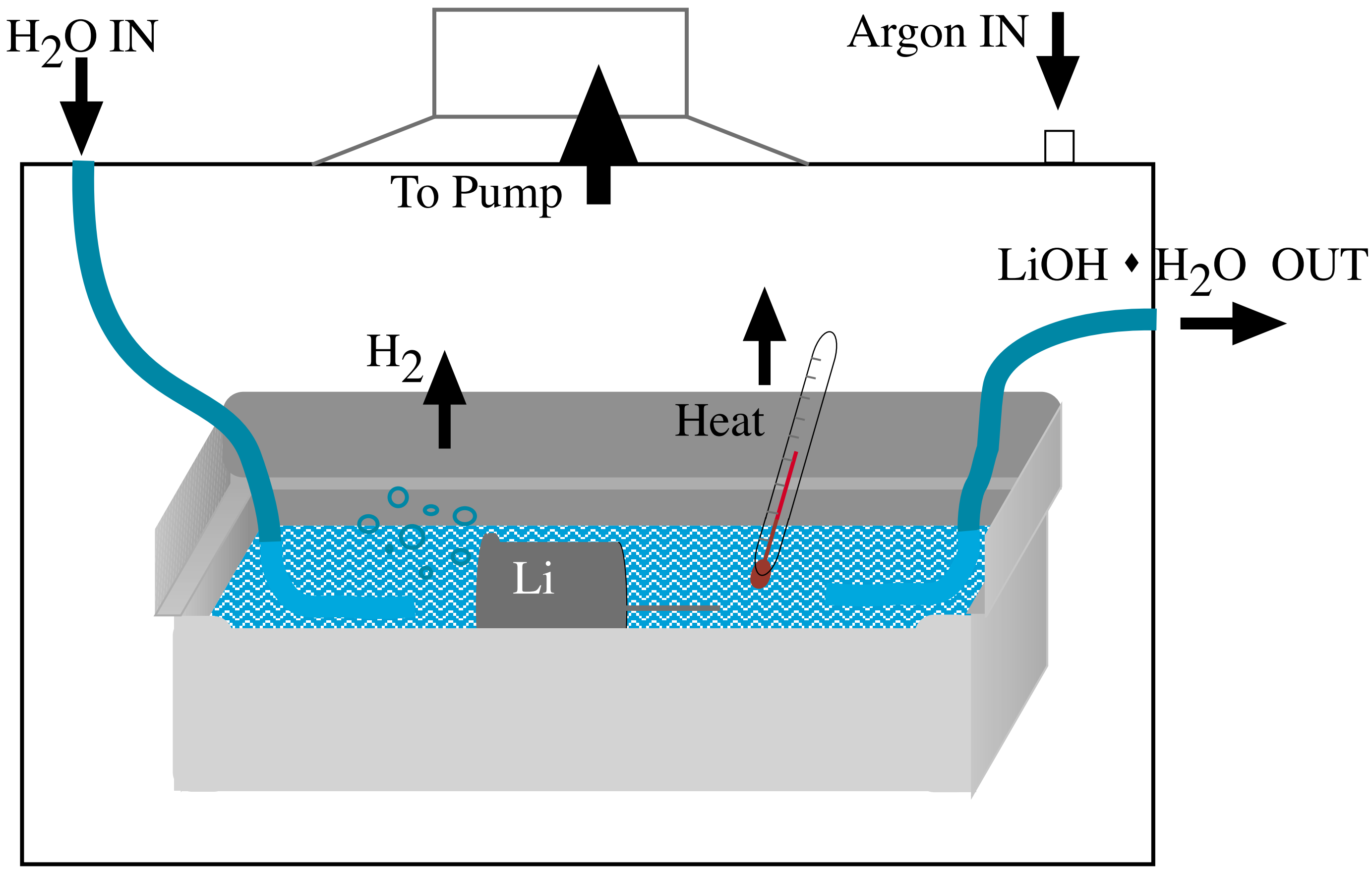
- Very stable arc discharge
- Self ignition at 80 V with cathode preheating
- No applied magnetic field
- Feed system and thruster performed well:
  - *Current: 500 A*
  - *Voltage: 20 V*
  - *Mass flow rate: 20 mg/s*
  - *Operating time: 3 min.*



Lithium Disposal Procedures

- Lithium disposal is accomplished by *chemical reaction* under a *controlled environment*.
  - Chamber interior, three stage process
    - *Ethanol vapor under vacuum.*
    - *Venting of Fumes*
    - *Water wipe down by operator using SCBA.*
  - Feed System components and tools.
    - *Inert argon atmosphere.*
    - *Continuous water flow to control temperature.*
- Reaction products collected in drums for disposal by EHS.

Lithium Disposal & Cleaning



$$Li + H_2O \Rightarrow LiOH \cdot H_2O + 1/2\ H_2 + \text{Heat (508 kJ/mole)}$$

Lithium Neutralization and Cleaning

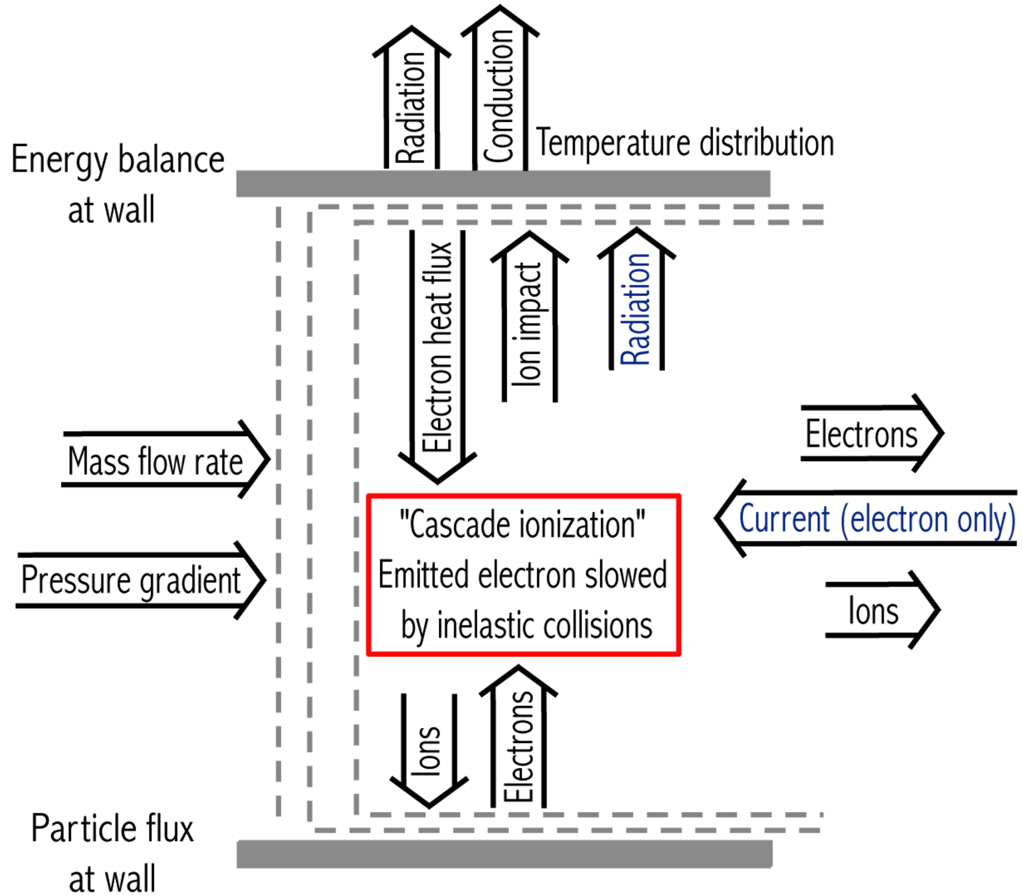
Diagnostics

Measurable Quantity	Controlling Parameters						Diagnostics
	$J^2/\dot{m}$	Ω_e	**Heat Flux**	**Att. Mode**	η	ξ	
V_A					X		Voltage Probe
J_A	X				X	X	Current Trans.
$\dot{m}_{Li}$	X				X	X	Feed System
B		X					Hall Probe
n_e		X					Langmuir Probe & Spectroscopy
T_e		X					
T_{anode}			X				Multi-color Pyrometry
ϕ_{anode}			X				Langmuir Probe
Thrust					X		Thrust Stand
$m_{ablated}$				X			High-Speed Photog. & Weight Measur.
species				X			Spectroscopy

Why the Multi-Channel Hollow Cathode?

- Cathode erosion limits lifetime in MPDTs
- MCHC demonstrates greatly reduced erosion
- MCHC shown to increase efficiency
- *Problem: No existing theoretical model*

Basic Elements of Proposed Model



Multi-Color Video Pyrometry

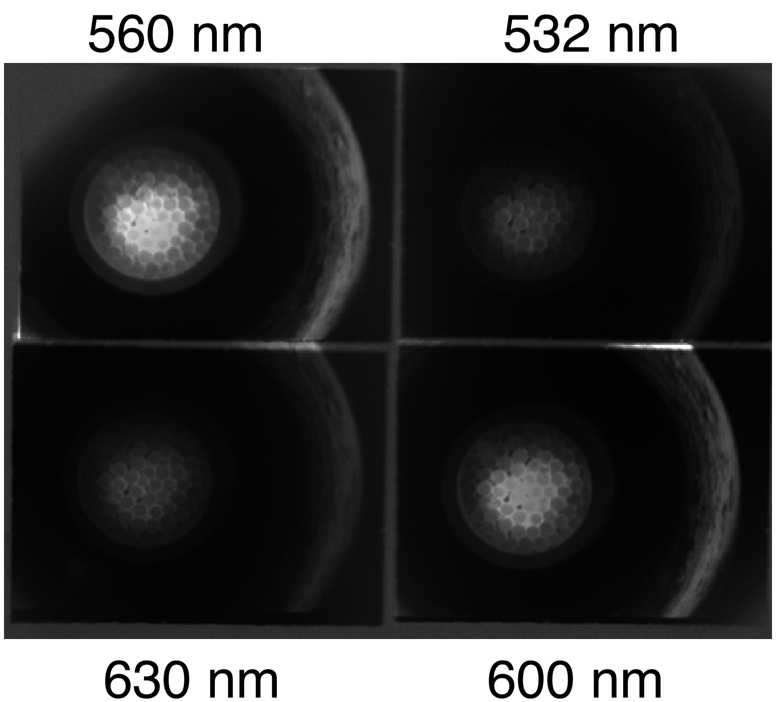
- Intensity measured at four wavelengths and data fit to appropriate intensity model:

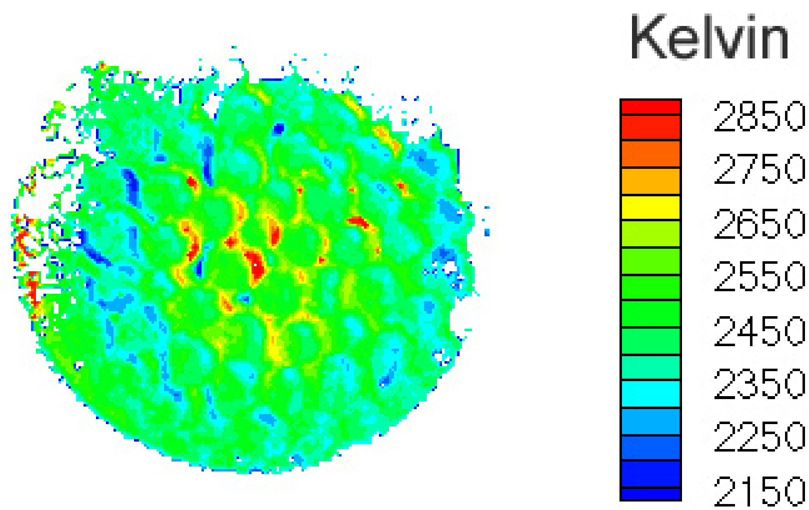
$$u(\lambda, T) = \underbrace{(a_0 + a_1\lambda)}_{\textit{Emissivity}} \underbrace{\frac{8\pi hc}{\lambda^5}\left(\frac{1}{e^{\frac{hc}{kT\lambda}} - 1}\right)}_{\textit{Planck's Law}}$$

- Image split four ways to pass through separate narrow bandwidth optical filters and recorded with a digital camera

MCVP Data

- MCVP views thruster end-on
- Cathode tip temperature 15 seconds after start-up:

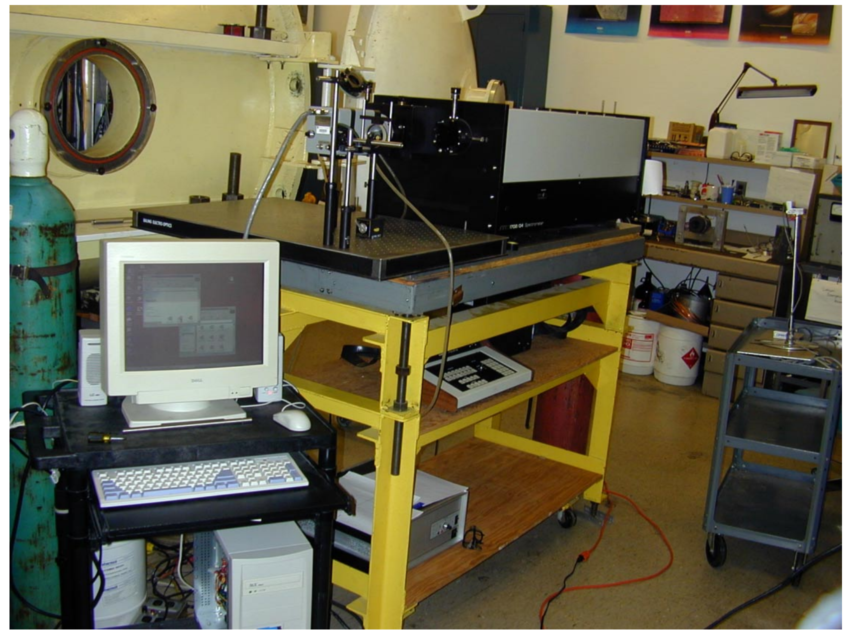




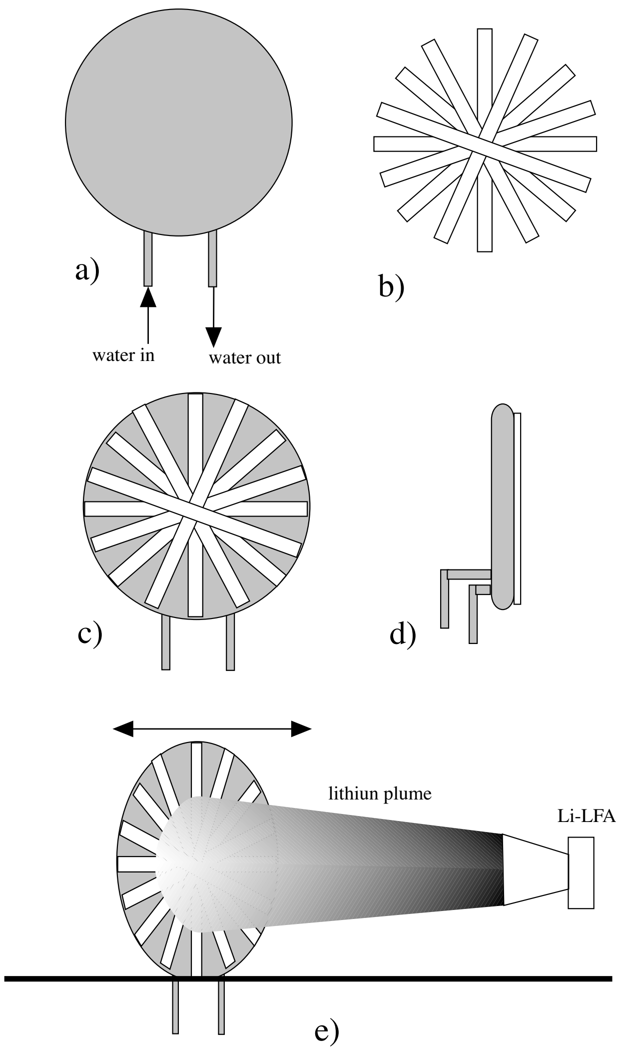
Spectroscopic Measurements

- Measurements of Te and ne

- Data Acquisition
  - Spex 1269 grating spectrometer
  - Princeton Instruments ICCD 576 CCD camera
- Data Manipulation
  - Software takes CCD images and converts into relative intensity vs. wavelength data
- Current Accomplishments
  - Setup and calibration of spectroscopic system
  - During first firing, approx. 20% of the visible spectrum acquired



Lithium Exhaust Flux Characterization



A New Numerical Model

Features:

- Time-dependent, multidimensional fluid model
- New accurate numerical scheme for the solution of MHD equations, with ability to capture shocks
- Relevant models for classical/anomalous transport, and a real equation of state
- For more information:
  - **IEPC-99-208**
  - **AIAA-00-2350** (Submitted to *International Journal of Numerical Methods in Engineering*)
  - **AIAA-00-3537**

Physical Model

- MHD equations (in conservation form)
  - Self-consistent treatment of flow & field equations
  - Relevant classical and anomalous transport properties

+

- Species energy equations
  - To account for thermal nonequilibrium between electrons and ions

+

- A real equation of state model
  - Necessary to model internal energy sinks

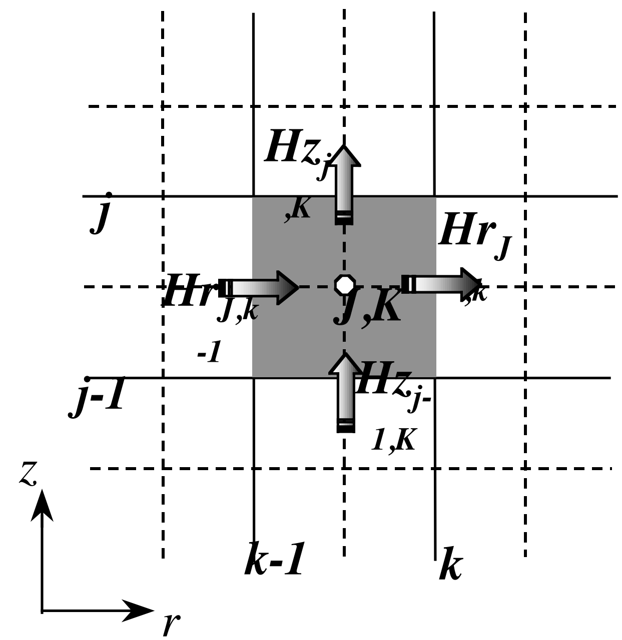
+

- Ionization model
  - Currently using an equilibrium ionization model: though not accurate, provides realistic results

Numerical Scheme

- Schemes for the dissipative part are well understood
- However there was a need for suitable schemes for the convective part:
  - Developed a characteristics-splitting scheme, that
    - » Evaluated fluxes using the propagation of MHD characteristics

$$\boxed{\mathbf{Hz}_{j+\frac{1}{2}} = \mathbf{Fz}_j^+ + \mathbf{Fz}_{j+1}^-}$$



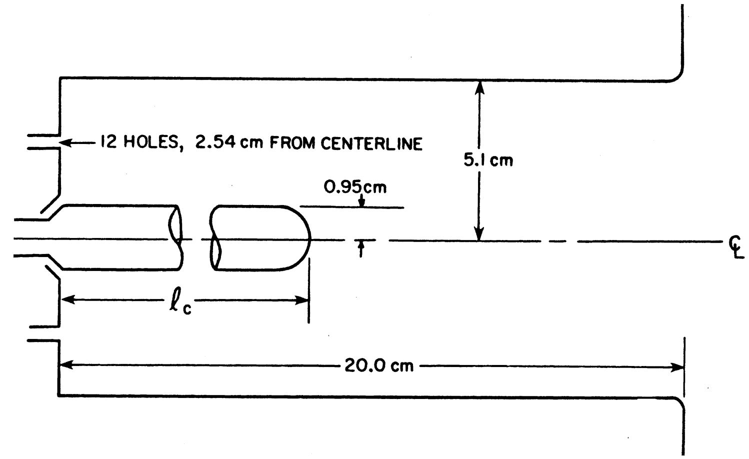
    - » Satisfied Rankine-Hugoniot jump conditions

$$\boxed{\Delta\mathbf{Fz}^{\pm} = \left[\mathbf{R}\Lambda^{\pm}\mathbf{R}^{-1}\right]\cdot\Delta\mathbf{U}}$$

    - » Was validated against standard test problems for unsteady and steady-state cases
      - **Riemann problem**
      - **Taylor state magnetic field configuration**

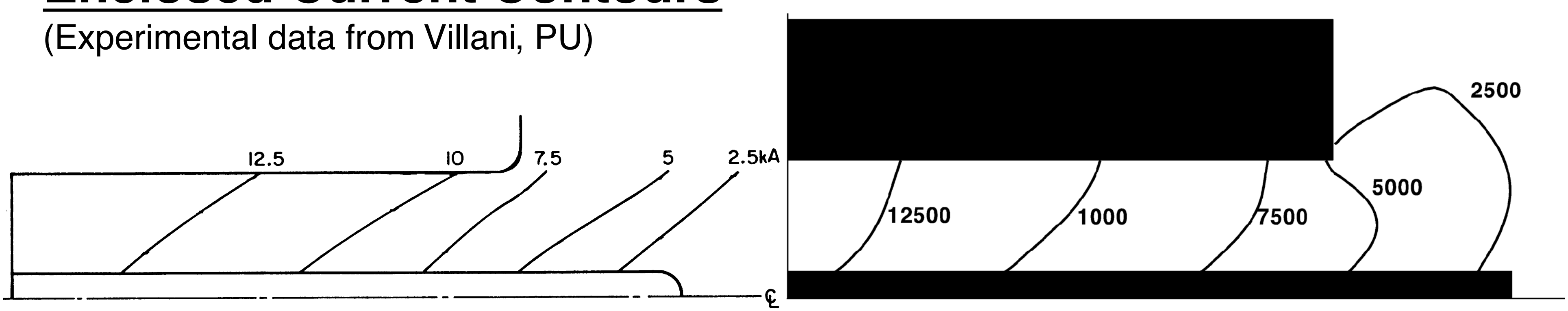
Comparison with Experimental Data

- Plasma flow in a constant area channel, coaxial MPDT was simulated
  - Propellant: argon
  - J = 15.0 kA
  - Mass flow rate: 6.0 g/s



Enclosed Current Contours

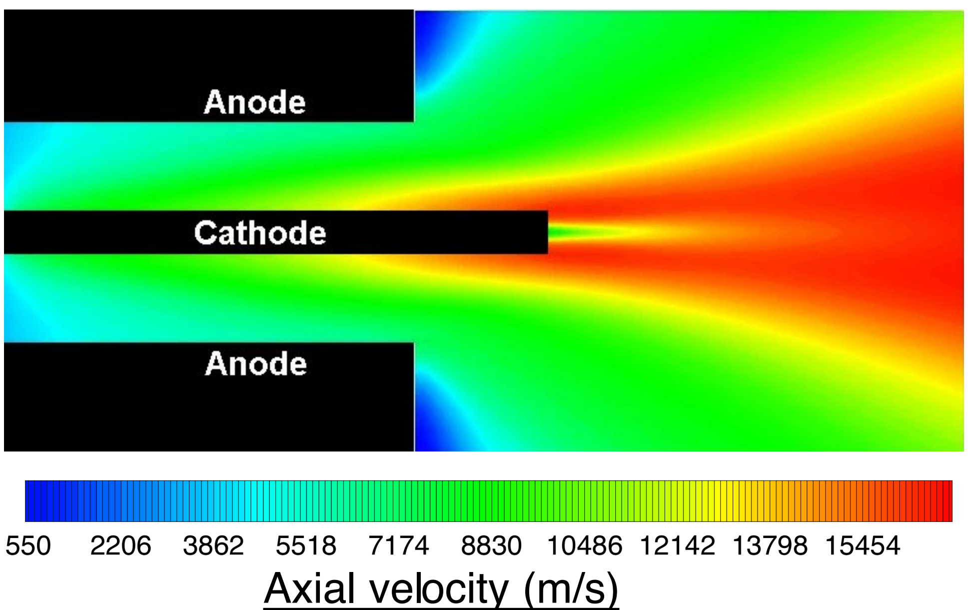
(Experimental data from Villani, PU)



Other Results

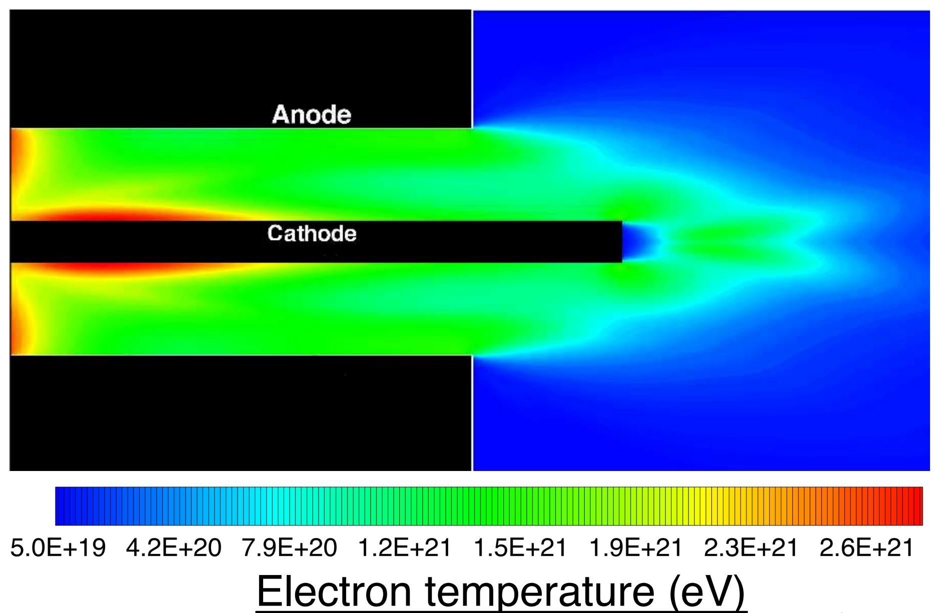
Velocity

- Increases with decreasing radius (within the chamber)
- Ranges from ~ 8km/s to ~14 km/s at the anode plane



Electron Density

- Effect of plasma pinching ($f_r = j_z B_\theta$) is clearly seen
- Ranges from ~ $10^{19}/m^3$ in the plume to ~ $3x10^{21}/m^3$ in near the cathode



Accomplishments and Future Goals

- *Met all technology development goals*
  - Lithium handling facilities
  - Neutralization, disposal and emergency procedures
  - Lithium feed system development
  - Specialized diagnostics
- *New thruster fired*
- *All sub-systems are operational*
- *Advanced plasma fluid code validated*

- *Studies of fundamental processes*

  (Results to be reported at JPC and IEPC 2001)